

Clinical and Procedural Determinants of Cumulative Air Kerma During Coronary Angiography and Percutaneous Coronary Intervention: A Prospective Observational Study

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ABSTRACT

Background

Radiation exposure remains an important safety concern during fluoroscopy-guided coronary procedures. Cumulative air kerma is a useful indicator of patient radiation exposure.

Objective

To identify clinical and procedural determinants of radiation exposure, measured as cumulative air kerma, during coronary angiography and percutaneous coronary intervention.

Method

We prospectively studied 723 consecutive patients undergoing coronary angiography and/or percutaneous coronary intervention between June 15, 2025, and June 15, 2026. Demographic, clinical, angiographic, procedural, and radiation exposure data were collected. Univariable analyses identified factors associated with log-transformed cumulative air kerma, followed by multivariable linear regression to determine independent predictors.

Result

Of 723 procedures, 353 (48.8%) were diagnostic coronary angiography and 370 (51.2%) were percutaneous coronary intervention. Procedure type, vascular access, fluoroscopy time, number of vessels and lesions treated, total stent length, and number of implanted stents was significantly associated with log-transformed cumulative air kerma in univariable analysis (all $p < 0.05$). The multivariable model was statistically significant ($p < 0.001$) and explained 69.6% of the variability in radiation exposure (adjusted $R^2 = 0.693$). Fluoroscopy time ($\beta = 0.495$, $p < 0.001$), percutaneous coronary intervention versus coronary angiography ($\beta = 0.390$, $p < 0.001$), female versus male sex ($\beta = -0.107$, $p < 0.001$), and femoral versus radial access ($\beta = -0.055$, $p = 0.009$) were independent predictors. Age, clinical indication, lesion type, and total stent length were not independently associated with cumulative air kerma.

Conclusion

Fluoroscopy time and procedure type were the strongest independent predictors of cumulative air kerma, highlighting procedural complexity as a major determinant of radiation exposure.

KEY WORDS

Coronary angiography, Fluoroscopy, Percutaneous coronary intervention, Radiation exposure

INTRODUCTION

Advances in device technology, expanding clinical indications, and improved procedural outcomes have led to substantial growth in interventional cardiology over the past few decades. As the number and complexity of fluoroscopy-guided coronary procedures have increased, patient exposure to ionizing radiation has also risen. Despite improvements in imaging technology and radiation protection measures, exposure to ionizing radiation remains necessary for coronary angiography (CAG) and percutaneous coronary intervention (PCI).^{1,2} Minimizing both deterministic and stochastic effects of radiation is still a key goal in modern catheterization labs, and optimizing radiation has become a standard practice.^{3,4}

Radiation exposure during coronary procedures results from a mix of patient characteristics, lesion complexity, procedural strategy, coronary anatomy, and operator technique. Together, these factors influence fluoroscopy time and imaging requirements, ultimately affecting the patient's radiation dose.⁵ Among the available dosimetric parameters, Cumulative Air Kerma (CAK) is commonly accepted as a reliable measure of patient radiation exposure because it shows the total radiation delivered during the procedure and correlates well with entrance skin dose. Unlike fluoroscopy time alone, CAK offers a more complete assessment of radiation burden during fluoroscopy-guided cardiac procedures.^{1,6}

In Nepal, the burden of cardiovascular disease has steadily increased, along with the expansion of catheterization laboratory services and greater access to PCI.⁷⁻¹¹ Despite this growth, there is limited data on the clinical and procedural factors related to patient radiation exposure during coronary procedures. To our knowledge, this is the first prospective study from Nepal to assess the clinical and procedural factors influencing CAK during CAG and PCI.

METHODS

This prospective observational study was conducted at Gautam Buddha Community Heart Hospital (GBCH) from June 15, 2025, to June 15, 2026. The study aimed to identify clinical and procedural CAK during CAG and PCI. All procedures were performed by consultant interventional cardiologists using a Siemens Artis One angiography system.

Adults aged ≥ 18 years who underwent CAG and/or PCI were consecutively screened for eligibility.

Inclusion criteria

Patients were included if they:

- Were aged 18 years or older.
- Underwent diagnostic coronary angiography and/or PCI during the study period.

- Had complete demographic, clinical, angiographic, procedural, and radiation dose data.

- Had cumulative Air Kerma successfully recorded by the angiography system.

Exclusion criteria

Patients were excluded if they:

- Were younger than 18 years.
- Underwent cardiac procedures other than coronary angiography or PCI.
- Had incomplete data on demographic, clinical, procedural, or radiation dose.
- Had coronary procedures requiring crossover from the initial radial approach to femoral access.
- Had a technical failure or interruption of the procedure resulting in an incomplete radiation dose recording.

Demographic, clinical, angiographic, procedural, and radiation-exposure data were prospectively collected using a standardized data collection form. Demographic variables included age and sex, while clinical variables included the indication for CAG or PCI. Angiographic characteristics included coronary artery disease severity and lesion complexity according to the American College of Cardiology/American Heart Association (ACC/AHA) lesion classification. Lesion classification was applied to lesions intended for treatment (PCI or POBA) and not to diagnostic CAG alone. Procedural variables included procedure type, vascular access site, fluoroscopy time, number of treated vessels and lesions, number of implanted stents, and total stent length. Ad hoc PCI, elective PCI, and POBA were grouped as PCI for the primary analysis because of their shared therapeutic nature and the small numbers in the elective PCI and POBA groups.

CAK was used as the primary measure of patient radiation exposure and was automatically recorded by the Siemens Artis One angiography system after each procedure. Because CAK was positively skewed, natural logarithmic transformation was performed before regression analyses.

The primary outcome was CAK. Candidate predictors included age, sex, vascular access site, procedure type (CAG or PCI), clinical indication, ACC/AHA lesion category, number of treated vessels, number of treated lesions, number of implanted stents, total stent length, and fluoroscopy time.

Sample size was calculated using G*Power version 3.1.9.7 (Heinrich Heine University Düsseldorf, Germany) for multiple linear regression (F tests; fixed model, R^2 deviation from zero).¹² Assuming a medium effect size (Cohen's $f^2 = 0.15$), $\alpha = 0.05$, power = 80%, and 11 candidate predictors, the minimum required sample was 123 participants. Because no comparable study provided sufficient data for direct estimation of effect size, a medium effect was

assumed. All consecutive eligible patients during the study period were enrolled, resulting in a final sample of 723 participants.

Statistical analyses were performed using IBM SPSS Statistics for Windows, version 22.0 (IBM Corp., Armonk, NY, USA). Continuous variables were assessed for distribution using the Shapiro–Wilk and Kolmogorov–Smirnov tests with Lilliefors correction, together with visual inspection of histograms. Normally distributed variables are presented as mean $\pm$ standard deviation (SD), and skewed variables as median with interquartile range (IQR). Categorical variables are reported as frequencies and percentages.

CAK demonstrated a positively skewed distribution (Shapiro–Wilk $P < 0.001$; skewness 3.394; kurtosis 18.242) and was therefore natural-log transformed. The transformed variable [ln(CAK)] demonstrated an approximately normal distribution (skewness -0.285 ; kurtosis 2.428) and was used as the dependent variable in subsequent analyses.

Univariable associations with ln(CAK) were assessed using simple linear regression for continuous variables and the General Linear Model for categorical variables. For categorical variables with more than 2 groups, one-way analysis of variance (ANOVA) with appropriate post hoc testing was performed when the overall comparison was significant.

Variables with $P < 0.20$ in univariable analyses, together with clinically relevant variables identified from previous literature, were considered for multivariable regression. Multicollinearity was assessed using Pearson correlation coefficients, variance inflation factors (VIFs), and tolerance values. Variables with substantial correlation ($r > 0.80$) were reviewed, and where necessary, the variable considered most clinically representative of procedural complexity was retained. A VIF > 5 or tolerance < 0.20 was considered indicative of significant multicollinearity.

Multiple linear regression was used to identify independent predictors of ln(CAK). Results are reported as unstandardized coefficients (B), standardized coefficients (β), 95% confidence intervals (CI), and P values. Model performance was assessed using R^2 , adjusted R^2 , the F statistic, and the Durbin–Watson statistic. Regression assumptions were evaluated using standardized residual plots, residual histograms, P–P plots, and plots of standardized residuals against predicted values. All tests were two-sided, with $P < 0.05$ considered statistically significant.

The study was approved by the Institutional Review Committee of Gautam Buddha Community Heart Hospital. Written informed consent for CAG and/or PCI was obtained from all patients as part of routine clinical practice. The study was conducted in accordance with the Declaration of Helsinki.

RESULTS

A total of 723 consecutive patients undergoing CAG and/or PCI were included in the study. The mean age was 58.7 ± 12.3 years, and 63.9% of participants were male. The demographic, clinical, angiographic, and procedural characteristics of the study population are summarized in table 1.

Table 1. Baseline demographic, clinical, angiographic and procedural characteristics of the study population (N = 723)

Characteristic	Value
Age, years	58.69 $\pm$ 12.29
Sex	
Male	462 (63.9)
Female	261 (36.1)
Clinical indication	
Non-specific chest pain	94 (13.0)
Chronic coronary syndrome	68 (9.4)
Unstable angina	63 (8.7)
NSTEMI	100 (13.8)
STEMI	398 (55.0)
Coronary angiography findings	
Normal coronary arteries	61 (8.4)
Minor coronary stenosis	68 (9.4)
Single-vessel disease	216 (29.9)
Double-vessel disease	182 (25.2)
Triple-vessel disease	196 (27.1)
Procedure performed	
Coronary angiography (CAG) only	353 (48.8)
PCI	370 (51.2)
Vascular access	
Radial	671 (92.8)
Femoral	52 (7.2)
Log-transformed cumulative Air Kerma, mean $\pm$ SD	6.35 $\pm$ 0.90
Fluoroscopy time (minutes) mean $\pm$ SD	8.44 $\pm$ 8.39
Mean cumulative Air Kerma (mGy) mean $\pm$ SD	843.4 $\pm$ 885.3
CAG	328.4 $\pm$ 162.3
PCI	1334.7 $\pm$ 1006.3
PCI characteristics*	
ACC/AHA lesion type (n = 370) [†]	
Type A	76 (20.5)
Type B	172 (46.5)
Type C	122 (33.0)
Number of vessels treated	1.09 $\pm$ 0.31
Number of lesions treated	1.15 $\pm$ 0.42
Total stent length, mm	32.58 $\pm$ 14.70

Data are presented as mean $\pm$ standard deviation or n (%).

PCI, percutaneous coronary intervention; NSTEMI, non-ST-segment elevation myocardial infarction; STEMI, ST-segment elevation myocardial infarction; ACC/AHA, American College of Cardiology/American Heart Association.

*ACC/AHA lesion classification applied only to patients with lesions undergoing lesion classification.

[†]Percentages are calculated among the 370 patients with classified coronary lesions, not the entire cohort.

The mean fluoroscopy time was 8.44 ± 8.39 minutes, while among patients with recorded stent-length data, the mean total stent length was 32.58 ± 14.70 mm. The mean cumulative Air Kerma for the entire study population was 843.4 ± 885.3 mGy. Patients undergoing PCI received significantly higher radiation doses than those undergoing diagnostic coronary angiography, with a mean Air Kerma of 1334.7 ± 1006.3 mGy compared with 328.4 ± 162.3 mGy, respectively ($p < 0.001$). The mean log-transformed cumulative Air Kerma was 6.35 ± 0.90 . Details regarding indications for coronary procedures, vascular access, lesion characteristics according to the ACC/AHA classification, procedural characteristics, and extent of coronary intervention are presented in table 1.

The histogram of the log-transformed variable (Fig. 1) demonstrated an approximately normal distribution.

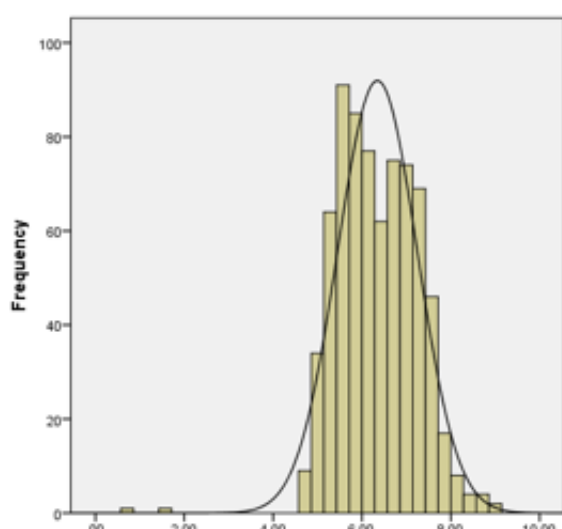


Figure 1. Distribution of log-transformed cumulative air kerma in the entire study population.

Univariate linear regression analysis was performed to examine the association between individual demographic, clinical, angiographic, and procedural variables and cumulative Air Kerma (CAK) expressed as log-transformed cumulative Air Kerma. The results are summarized in table 2.

Age was not significantly associated with log-transformed radiation dose ($\beta = 0.004$, $SE = 0.003$, standardized $\beta = 0.055$, $t = 1.482$, $p = 0.139$). Gender was significantly associated with log-transformed radiation dose. Compared with male sex, female sex was independently associated with lower cumulative Air Kerma sex ($\beta = -0.389$, 95% CI -0.522 to -0.255 ; standardized $\beta = -0.209$; $p < 0.001$).

One-way ANOVA showed a significant difference in mean log-transformed radiation dose among the five clinical indication groups ($F(4,718) = 33.249$, $p < 0.001$). Post hoc analysis showed that patients undergoing intervention for STEMI had significantly higher radiation doses than those with non-specific chest pain, chronic coronary syndrome, unstable angina, and NSTEMI (all $p \leq 0.001$). NSTEMI procedures were also associated with significantly higher

radiation doses than procedures performed for non-specific chest pain ($p < 0.001$). No significant differences were observed between non-specific chest pain, chronic coronary syndrome, unstable angina, and NSTEMI for the remaining pairwise comparisons.

In the univariate linear regression analysis, vascular access was significantly associated with log-transformed cumulative Air Kerma. Femoral access was associated with higher radiation exposure than radial access ($B = 0.365$, 95% CI: 0.114 – 0.616 ; $p = 0.005$). This changed significantly after adjusting for other variables in multivariate analysis.

Procedure type was significantly associated with log-transformed radiation dose in the univariate analysis (one-way ANOVA: $F = 274.05$, $p < 0.001$), explaining 53.3% of the variability in CAK ($R^2 = 0.533$). Mean log transformed CAK varied significantly across procedure types. Diagnostic CAG was associated with the lowest mean log transformed CAK (5.679 ; 95% CI, 5.615 – 5.743), whereas plain old balloon angioplasty (POBA) had the highest mean log transformed CAK (7.328 ; 95% CI, 6.994 – 7.662).

Table 2. Univariate analysis of clinical and procedural factors associated with log-transformed cumulative Air Kerma during coronary angiography and percutaneous coronary intervention

Variable	Analysis	Effect estimate	p-value
Age	Linear regression	$B = 0.004$ (95% CI -0.001 to 0.009)	0.139
Gender	Linear regression	$B = -0.389$ (95% CI -0.522 to -0.255)	< 0.001
Vascular access	Linear regression	$B = 0.365$ (95% CI: 0.114 – 0.616)	0.005
Procedure type (PCI vs CAG)	Linear regression	$B = 1.305$ (95% CI: 1.215 – 1.395)	< 0.001
Indication	One-way ANOVA	$F(4,718) = 33.25$	< 0.001
ACC/AHA lesion category	One-way ANOVA	$F(3,719) = 47.36$	< 0.001
Number of vessels treated	Linear regression	$B = 0.326$ (95% CI: 0.095 – 0.557)	0.006
Number of treated lesions	Linear regression	$B = 0.293$ (95% CI: 0.126 – 0.460)	0.001
Number of implanted stents	Linear regression	$B = 0.898$ (95% CI: 0.822 – 0.974)	< 0.001
Total stent length	Linear regression	$B = 0.008$ (95% CI: 0.004 – 0.012)	0.002
Fluoroscopy time	Linear regression	$B = 0.080$ (95% CI 0.075 to 0.085)	< 0.001

Values are presented as unstandardized regression coefficients (B) with 95% confidence intervals for linear regression analyses, F statistics for one-way ANOVA. Post hoc comparisons were performed using Tukey HSD or Games–Howell tests where appropriate.

Post hoc Tukey analysis showed that elective PCI, ad hoc PCI, and POBA each had significantly higher radiation exposure than diagnostic coronary angiography (all $p < 0.001$). In contrast, we didn't find significant differences among the three PCI procedures (all $p > 0.05$).

When comparing CAG vs PCI (including all PCI, POBA in a single interventional category), an independent-samples Welch's t-test demonstrated a significant difference in log-transformed Air Kerma between CAG and PCI procedures ($t = -28.73$, $df = 687.9$, $p < 0.001$). The mean difference was -1.305 (95% CI: -1.394 to -1.216), indicating substantially higher radiation exposure during PCI.

One-way ANOVA demonstrated a significant difference in mean log-transformed radiation dose among ACC/AHA lesion types ($F(3,719) = 47.360$, $p < 0.001$). Because the assumption of homogeneity of variances was violated (Levene's test $p < 0.001$), Games–Howell post hoc comparisons were performed. Radiation dose was significantly lower in patients with normal coronary arteries than in those with Type A, Type B, or Type C lesions (all $p < 0.001$). Type B lesions were associated with significantly higher radiation doses than Type C lesions ($p = 0.005$). In contrast, no significant differences were observed between Type A and Type B or between Type A and Type C lesions.

Procedural variables including number of vessels treated, number of lesions treated, total stents placed, and total stent length were all significantly associated with increasing cumulative Air Kerma (CAK).

Among all candidate predictors, fluoroscopy time demonstrated the strongest association with log-transformed cumulative Air Kerma, followed by procedure performed, indicating that increasing procedural complexity was associated with progressively higher cumulative Air Kerma.

Variables showing significant associations in univariate analysis, together with clinically relevant covariates, were entered into the initial multivariable linear regression model. After assessing multicollinearity, variables representing procedural complexity (number of vessels treated, number of lesions treated, and total stents implanted) showed substantial multicollinearity and were therefore excluded from the final model. The final regression model was statistically significant ($F = 204.73$, $p < 0.001$) and explained 69.6% of the variability in CAK ($R^2 = 0.696$; adjusted $R^2 = 0.693$). The Durbin–Watson statistic was 1.958, indicating no evidence of autocorrelation among model residuals.

After multivariable adjustment, fluoroscopy time remained the strongest independent predictor of cumulative Air Kerma ($\beta = 0.511$, $B = 0.054$, 95% CI 0.049 – 0.060 ; $p < 0.001$). Procedure performed was also independently associated with higher cumulative Air Kerma (CAK) ($\beta = 0.358$, $B = 0.219$, 95% CI 0.163 – 0.275 ; $p < 0.001$). Compared with diagnostic coronary angiography, PCI was associated with a significantly higher radiation dose ($B = 0.698$, $\beta = 0.390$, 95% CI: 0.553 – 0.843 , $p < 0.001$), indicating that interventional procedures contribute substantially to patient radiation exposure even after accounting for fluoroscopy time and lesion characteristics. In addition, gender ($\beta = -0.106$, $B = -0.199$, 95% CI -0.277 to -0.121 ;

$p < 0.001$) and vascular access ($\beta = -0.059$, $B = -0.207$, 95% CI -0.353 to -0.060 ; $p = 0.006$) remained significant independent predictors of cumulative Air Kerma (CAK). Female patients had significantly lower Air Kerma than male patients after adjustment for procedural factors. Femoral access was associated with lower log-transformed Air Kerma than radial access after adjustment for other variables. In the unadjusted analysis, femoral access was associated with significantly higher log-transformed Air Kerma and longer fluoroscopy time than radial access. However, after adjustment for procedural and clinical covariates, femoral access was associated with lower adjusted radiation exposure. This finding indicates that the crude association was influenced by confounding from procedural characteristics, particularly the distribution of more complex procedures and differences in fluoroscopy duration between access groups. These results underscore the importance of multivariable adjustment when evaluating the relationship between vascular access and patient radiation exposure. Conversely, age ($p = 0.400$), indication for the procedure ($p = 0.393$), ACC/AHA lesion classification ($p = 0.418$), and total stent length ($p = 0.177$) were not independently associated with CAK after adjustment for other variables. Our cohort didn't reveal significant multicollinearity among the variables included in the final multivariable model. Variance inflation factors ranged from 1.038 to 3.737, while tolerance values ranged from 0.268 to 0.964, indicating acceptable collinearity among the predictor variables. Details of multivariate analysis are presented in table 3.

Table 3. Multiple linear regression analysis of factors associated with log-transformed cumulative Air Kerma (N = 723).

Variable	Adjusted B	SE	Standardized β	95% CI	p-value
Age (years)	-0.001	0.002	-0.018	-0.004 to 0.002	0.386
Female sex (vs male)	-0.199	0.039	-0.107	-0.276 to -0.123	<0.001
Indication	0.012	0.016	0.019	-0.020 to 0.043	0.462
Fluoroscopy time (minutes)	0.053	0.003	0.495	0.047 to 0.058	<0.001
PCI (vs CAG)	0.698	0.074	0.390	0.553 to 0.843	<0.001
Femoral access (vs radial)	-0.191	0.073	-0.055	-0.334 to -0.048	0.009
ACC/AHA lesion type	0.014	0.020	0.017	-0.024 to 0.053	0.473
Total stent length (mm)	0.001	0.002	0.028	-0.002 to 0.005	0.437

Model statistics: $F(8,714) = 204.73$, $p < 0.001$; $R^2 = 0.696$; adjusted $R^2 = 0.693$; Durbin–Watson = 1.958. No evidence of significant multicollinearity was observed (VIF range: 1.038–3.737).

Table 4 shows the distribution of cumulative Air Kerma according to procedure type and vascular access. As expected, PCI was associated with substantially higher radiation exposure than diagnostic coronary angiography, irrespective of the access site.

Table 4. Mean Cumulative Air Kerma according to procedure type and vascular access

Procedure	Radial (n)	Radial Air Kerma (mGy) Mean $\pm$ SD	Femoral (n)	Femoral Air Kerma (mGy) Mean $\pm$ SD
CAG	340	328.9 $\pm$ 160.8	13	316.8 $\pm$ 206.2
PCI	331	1299.0 $\pm$ 875.8	39	1637.8 $\pm$ 1751.7
Overall	671	807.4 $\pm$ 791.5	52	1307.6 $\pm$ 1621.7

Among patients undergoing diagnostic CAG, the mean Air Kerma was similar between radial and femoral access (328.9 $\pm$ 160.8 mGy vs. 316.8 $\pm$ 206.2 mGy). In contrast, among PCI procedures, the mean Air Kerma was higher with femoral access than radial access (1637.8 $\pm$ 1751.7 mGy vs. 1299.0 $\pm$ 875.8 mGy). Overall, procedures performed via the femoral approach were associated with a higher mean Air Kerma than those performed via the radial approach (1307.6 $\pm$ 1621.7 mGy vs. 807.4 $\pm$ 791.5 mGy). This finding changed significantly after doing multivariate analysis, emphasizing again that CAK depends on multiple factors rather than vascular access only.

DISCUSSIONS

In our cohort, procedural characteristics explained substantially more variation in Cumulative Air Kerma than baseline patient characteristics, indicating that radiation exposure is driven primarily by procedural rather than patient-related factors. Although several clinical and procedural variables were associated with radiation exposure in univariate analyses, only fluoroscopy time, procedure type, sex, and vascular access remained independent predictors after multivariable adjustment.

Among all variables examined, fluoroscopy time showed the strongest association with CAK, reinforcing its central role in determining patient radiation exposure during coronary procedures. Anatomical and procedural complexity markers, including lesion complexity, number of treated vessels, number of treated lesions, total number of stents implanted, and cumulative stent length, were associated with higher radiation exposure in unadjusted analyses but were no longer significant after adjustment.

Fluoroscopy Time as the Primary Determinant of Radiation Exposure

We found fluoroscopy time was the strongest independent predictor of CAK during CAG and PCI. Even after adjustment for demographic characteristics, clinical indication, lesion complexity, vascular access, and other procedural variables, this association was significant. Our results are

consistent with previous evidence demonstrating that prolonged fluoroscopic imaging is a major contributor to patient radiation exposure during interventional cardiology procedures.^{1,6}

Fluoroscopy time reflects both radiation use and procedural complexity. Although it does not account for all determinants of patient dose, such as cine acquisition, imaging angles, patient habitus, and X-ray system settings, it remains a practical marker of the intensity and duration of image-guided intervention.^{13,14} The strong relationship observed in our study likely represents the cumulative effect of prolonged imaging during technically demanding procedures.

Previous studies have similarly demonstrated the close relationship between fluoroscopy duration and radiation exposure. Fetterly et al. showed that longer fluoroscopy time was strongly associated with increased radiation dose but emphasized that other factors, including acquisition protocols, beam angulation, patient characteristics, and equipment settings, also influence cumulative exposure.¹³ Vañó et al. further highlighted the contribution of prolonged fluoroscopic imaging during complex interventions requiring repeated angiographic acquisitions and device manipulation.¹⁴

Current radiation protection recommendations from the International Commission on Radiological Protection (ICRP) and cardiovascular imaging consensus guidelines recognize fluoroscopy time as an important indicator of radiation exposure but caution that it should not be considered a surrogate for dose alone. Cumulative air kerma and dose-area product provide a more comprehensive assessment because they incorporate additional factors affecting radiation burden.^{1,6} Chronic total occlusions, bifurcation lesions, severe calcification, multivessel disease, and complex device strategies often require prolonged wire manipulation, lesion preparation, multiple stent deployments, and repeated angiographic assessments, all contributing to increased radiation exposure.^{14,15}

Several variables associated with radiation exposure in univariate analysis, including lesion complexity, number of treated lesions, number of stents, and total stent length, did not remain significant after adjustment for fluoroscopy time. This indicates that fluoroscopy duration acts as an integrative measure through which multiple aspects of procedural complexity influence radiation exposure.

Although fluoroscopy duration cannot always be shortened in technically challenging cases continuous awareness of radiation dose and adherence to the ALARA principle remain essential components of radiation protection in the catheterization laboratory.^{1,16}

Recent studies support the effectiveness of fluoroscopy optimization strategies. Costa et al. demonstrated that fluoroscopy time remained an independent predictor of cumulative air kerma in complex PCI despite adjustment for

other procedural variables.¹⁷ Gupta et al. further showed that implementing a very low frame-rate fluoroscopy protocol significantly reduced radiation exposure without compromising procedural success, emphasizing the impact of simple technical modifications.¹⁸ Allahwala et al. demonstrated that patient-related factors, particularly body mass index, may influence cumulative air kerma even with similar fluoroscopy durations.¹⁹ Therefore, cumulative air kerma remains the most appropriate measure for evaluating overall patient radiation exposure.

Procedural characteristics were important determinants of cumulative air kerma in the present study. In univariate analyses, procedure type, ACC/AHA lesion classification, number of treated vessels, number of treated lesions, number of implanted stents, and total stent length were associated with radiation exposure. However, after multivariable adjustment, only procedure type remained an independent predictor. This suggests that although procedural complexity contributes to radiation exposure, much of its effect is mediated through longer fluoroscopy time and the overall demands of the intervention. Previous studies have demonstrated that cumulative air kerma during PCI is generally two- to three-fold higher than during diagnostic CAG. However, absolute values vary according to patient characteristics, procedural complexity, operator experience, imaging protocols, and available technology.^{14,15,17}

Subban et al., in a multicenter Indian study, reported median cumulative air kerma values of 185 mGy for diagnostic coronary angiography and 533 mGy for PCI.²⁰ Similarly, Ngaile et al. observed median values of 425.5 mGy for angiography and 1180.3 mGy for PCI in Tanzania, while Al-Jabri et al. reported median cumulative air kerma values of 0.86 Gy for coronary angiography and 2.6 Gy for PCI in Oman.^{21,22} Ghosn et al. reported typical cumulative air kerma values of 260 mGy for CAG and 877 mGy for PCI.²³ In comparison, Kulkarni et al. reported local reference values of 590 mGy and 1930 mGy, respectively.^{23,24} These variations highlight the influence of local practice patterns, patient characteristics, operator experience, and radiation optimization protocols on patient exposure.

In our study, procedure type remained independently associated with CAK even after adjustment for fluoroscopy time and other covariates.

Lesion complexity and procedural burden were associated with higher CAK in univariate analyses. Complex lesions often require prolonged guidewire manipulation, additional lesion preparation, multiple device exchanges, and repeated angiographic assessments. Similarly, treatment of multiple vessels or lesions, implantation of multiple stents, and greater total stent length were associated with increased radiation exposure before adjustment.

The results are consistent with previous evidence demonstrating the relationship between procedural

complexity and radiation dose. More challenging coronary interventions generally require longer fluoroscopic guidance and increased cine acquisition, both of which directly contribute to cumulative air kerma.^{1,15,16} Evidence from large registries further supports the association between lesion complexity and radiation exposure. In a Thai registry including 22,737 PCI procedures, Srimahachota et al. demonstrated a progressive increase in cumulative air kerma with increasing ACC/AHA lesion complexity.²⁵ Median cumulative air kerma increased from 790 mGy for type A lesions to 1705 mGy for type C lesions, with type C lesions requiring more than twice the radiation exposure observed with type A lesions.²⁵

However, in our multivariable analysis, lesion complexity, number of treated vessels, number of treated lesions, and total stent length did not remain independent predictors after adjustment for fluoroscopy time and procedure type. This suggests that anatomical complexity influences radiation exposure mainly by increasing procedural duration rather than through an independent effect on radiation dose. The findings are consistent with past studies where fluoroscopy time accounted for much of the association between procedural complexity and radiation exposure.^{14,17,18} Although lesion complexity is an important contributor, radiation exposure is also influenced by multiple patient-, procedure-, operator-, and equipment-related factors, including body habitus, imaging protocols, fluoroscopy frame rate, equipment characteristics, and operator practice patterns.^{26,27} Importantly, registry data have shown that radiation exposure can decrease over time despite increasing procedural complexity, suggesting that technological advances, improved workflows, and operator experience can reduce the additional radiation burden associated with complex interventions.²⁸ Taken together, the current analysis indicates that procedural complexity affects radiation exposure primarily through its impact on fluoroscopy duration. Therefore, radiation optimization should focus not only on reducing fluoroscopy time but also on improving procedural planning and efficiency, particularly during complex PCI. Strategies such as appropriate device selection, optimized fluoroscopy settings, lower frame rates, effective collimation, and adherence to the ALARA principle may reduce patient radiation exposure without compromising procedural outcomes.^{1,16,18}

Vascular access was independently associated with CAK in the multivariable regression model, although its effect was modest compared with fluoroscopy time and procedure type. In contrast, access site was not significantly associated with cumulative air kerma in the two-way ANOVA, and no significant interaction was observed between vascular access and procedure type. This difference may reflect the influence of case selection and procedural complexity, as femoral access is often used in patients requiring complex interventions or when radial access is not feasible. The relationship between vascular access

and radiation exposure remains debated. Earlier studies suggested that transradial access was associated with longer fluoroscopy times and increased radiation exposure, particularly during the early adoption of radial techniques, when operator experience was limited.^{29,30} However, subsequent randomized trials and observational studies have demonstrated minimal or no significant difference in cumulative air kerma between radial and femoral access, particularly for diagnostic coronary angiography.^{31,32} Some studies have reported slightly higher radiation exposure with transradial PCI, especially in lower-volume radial programs, likely reflecting technical challenges and operator learning curves.^{5,33} With increasing operator experience and the development of high-volume radial programs, these differences appear to diminish. Studies from experienced centers have demonstrated comparable or even lower radiation exposure with radial access when optimized techniques and radiation-saving strategies are applied.^{34,35}

Although vascular access remained statistically significant in multivariable analysis, its contribution to radiation exposure was considerably smaller than that of fluoroscopy time and procedure type. Current recommendations therefore emphasize that vascular access selection should primarily be guided by clinical factors, including patient characteristics, bleeding risk, procedural requirements, and operator expertise, rather than radiation concerns alone.^{1,14}

Among the patient-related variables evaluated in our study, after adjustment for clinical and procedural variables, male sex remained independently associated with higher CAK, whereas age showed no significant independent association. The results suggest that patient characteristics may influence radiation dose, but their contribution is relatively small compared with procedural determinants, particularly fluoroscopy time and procedure type. The association between male sex and higher CAK has been reported previously. This relationship may be related to differences in body habitus, as greater tissue attenuation requires increased X-ray output to maintain image quality. In addition, male patients may have more complex coronary anatomy or a higher likelihood of undergoing technically challenging procedures, potentially contributing to increased radiation exposure. Although procedural factors were included in our model, the persistent association suggests that patient size and imaging requirements partly explain this finding. Our findings align with previous reports examining factors associated with radiation exposure during interventional cardiology procedures.^{1,15,19}

Although older age was associated with higher CAK in univariate analysis, this relationship did not remain significant after multivariable adjustment. This suggests that age itself is unlikely to influence radiation exposure directly. Instead, increased radiation exposure among

older patients may reflect greater disease complexity and more challenging procedures, which are better captured by procedural variables such as fluoroscopy time and intervention type. Similar findings have been reported in the past after adjustment for procedural characteristics.^{17,19}

The findings in this cohort have important implications for radiation safety in cardiac catheterization laboratories. As fluoroscopy time and procedure type were the strongest determinants of CAK, radiation reduction efforts should focus on minimizing unnecessary imaging while maintaining procedural quality and patient safety. Strategies including careful pre-procedural planning, judicious fluoroscopy use, reduction of unnecessary cine acquisitions, appropriate frame-rate selection, optimal collimation, avoidance of unnecessary magnification, and adherence to the ALARA principle may help reduce patient radiation exposure. Identifying procedures likely to require prolonged fluoroscopy, particularly complex PCI, may allow early implementation of radiation-saving measures. The results are particularly relevant in Nepal, where interventional cardiology services and procedural complexity are increasing. Regular radiation safety training, operator awareness, routine dose monitoring, and implementation of standardized radiation optimization protocols may improve patient and operator safety without compromising procedural outcomes.

Our study has several strengths. To our knowledge, it is the first prospective study from Nepal evaluating clinical and procedural determinants of cumulative Air Kerma during coronary angiography and PCI. The prospective design, relatively large sample size, inclusion of consecutive real-world procedures, and assessment of multiple clinical and procedural variables allowed a comprehensive evaluation of factors influencing radiation exposure. Furthermore, multivariable regression analysis enabled identification of independent predictors while accounting for potential confounding factors.

Several limitations should be acknowledged. First, this was a single-center study, and the findings may not be fully generalized to institutions with different patient populations, operator experience, and procedural practices. Second, although procedures were performed by experienced interventional cardiologists using the same angiography system, operator-specific factors, including fluoroscopy settings, cine acquisition practices, projection selection, and procedural techniques, were not evaluated and may have influenced radiation exposure.

Third, cumulative Air Kerma was used as the primary radiation metric. Although widely accepted for assessing patient radiation burden, it does not directly represent effective dose or peak skin dose. Fourth, important variables such as body mass index, body habitus, fluoroscopic angulations, use of radiation-reduction technologies, and contrast volume were unavailable and

may have contributed to residual confounding. Finally, the observational design limits causal interpretation despite adjustment for multiple clinical and procedural factors, and dose-area product was not available for analysis.

CONCLUSION

In this prospective study of coronary angiography and PCI, fluoroscopy time was the strongest independent determinant of cumulative Air Kerma, highlighting the central role of procedural technique in patient radiation exposure. Procedure type, sex, and vascular access were also independently associated with radiation dose, although their effects were smaller compared with fluoroscopy duration.

Our findings provide important baseline data on radiation exposure during cardiac catheterization procedures in Nepal. Improving fluoroscopy practices, optimizing procedural workflow, and maintaining radiation awareness through operator training and standardized dose-reduction protocols are essential strategies to minimize patient

radiation exposure as interventional cardiology services continue to expand.

Differences in patient demographics, healthcare infrastructure, and procedural protocols could affect the applicability of our results elsewhere. While our findings provide valuable insights applicable to similar resource-limited settings, multicenter studies across diverse populations would be necessary to confirm the broader relevance of our conclusions.

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